Predictions of Helmet Pad Suspension System Performance Using Isolated Pad Impact Results

J. Hopping[1], J. Zheng[1], S. Bosselman[1], K. Masters[1] and C. Perritt[1]

[1]Technical Management Division (TMD), Project Manager Soldier Protection and Individual Equipment (PM SPIE), 15395 John Marshall Hwy Haymarket, VA 20169
jakob.a.hopping@us.army.mil

Abstract. The Advanced Combat Helmet (ACH) pad suspension system is the primary attenuator of low-rate blunt impacts to a Soldier's head. Quantification of pad suspension system improvements currently requires the costly and time consuming testing of an entire helmet. Two potential methodologies for independently testing pads were assessed using four existing pad designs. One of these methodologies used a flat anvil impact surface, and the other used a modular elastomer pad (MEP) impact surface. Independent pad testing was conducted at three environmental and four impact velocity conditions. These test results were compared to those from complete helmet tests under the same environmental conditions and three of the four impact velocity conditions. This comparison shows that ambient (295 ^{o}K) temperature, 3.0 m/s independent pad impacts on a MEP surface account for over 99% of the variation observed in ambient (295 ^{o}K) temperature, 3.0 m/s complete system impacts. Under the same conditions, the flat anvil impact surface results account for 92% of the variation seen in complete system impacts. Despite positive results under ambient conditions, independent pad impacts are not a useful predictor of pad suspension system performance under extreme high or low temperatures. For example, hot (327 ^{o}K) temperature, 3.0 m/s independent pad impacts on a MEP surface account for only 31% of the variation observed in hot (327 ^{o}K) temperature, 3.0 m/s complete system impacts. Under the same conditions, flat anvil impact results account for only 4.4% of the variation seen in system impacts. At extreme temperature conditions, interactions of the helmet or impact surface with the pad suspension system likely contribute significantly to the end result. Independent impacts become progressively less valuable as a predictor of helmet system results as the impact temperature condition becomes increasingly extreme, and future studies will assess alternative test setups that may eliminate this drawback.

1. INTRODUCTION

The Advanced Combat Helmet (ACH), see Figure 1, is the primary head protection for the dismounted U.S. Soldier. In accordance with the purchase description, the ACH provides specified levels of ballistic penetration protection, ballistic impact protection, and low-rate blunt impact protection [1]. The ACH has seven major components: helmet shell, pad suspension system, chinstrap retention system with hardware, helmet cover, eyewear retention strap, nape pad, and night vision device mounting bracket [2]. Because the ACH shell is sufficiently rigid, the shell has little influence on the attenuation of low-rate blunt impacts to the head. Therefore, the low-rate blunt impact performance of the ACH is principally due to the performance of the pad suspension system. The ACH pad suspension system is the primary attenuator of low-rate blunt impacts to the head of a U.S. Soldier, and the main component of the ACH pad suspension system is the pad itself.

There are three different pad shapes that form the suspension system: round, trapezoidal, and oblong. Each of these pad shapes is identical in composition; they vary only by shape [3]. A complete pad suspension kit consists of seven (nine with the XXL helmet) pads: one round pad (placed on the crown of the helmet), two trapezoidal pads (placed on the front and back of the helmet), and four (six for XXL helmets) oblong pads (distributed around the perimeter of the helmet to achieve comfort and stability) [4]. Although all seven pads are necessary to provide required impact protection, the performance of an individual pad may be indicative of the performance for the pad suspension system.

Testing the performance of a particular pad suspension system candidate traditionally must occur with the use of a complete helmet. The testing process irreversibly damages the helmet shell used; thus, one helmet shell is destroyed for every pad suspension system test. Material cost for the complete helmet is 450 percent greater than for the isolated pad suspension system (approximately $220 per helmet versus $40 per complete pad suspension system). Because of material cost, it is desirable to evaluate pad suspension system performance independent of the ACH. Test equipment setup for independent pad suspension

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **13 SEP 2010**	2. REPORT TYPE **Final**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Predictions of Helmet Pad Suspension System Performance Using Isolated Pad Impact Results**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Jakob A Hopping; James Q Zheng; Suzanne Bosselman; Karl Masters; and Chris Perritt**	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Technical Management Division, Project Manager Soldier Protection and Individual Equipment 15395 John Marshall Hwy Haymarket, VA 20169**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Personal Armour System Symposium 2010(PASS 2010)**	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The Advanced Combat Helmet (ACH) pad suspension system is the primary attenuator of low-rate blunt impacts to a Soldiers head. Quantification of pad suspension system improvements currently requires the costly and time consuming testing of an entire helmet. Two potential methodologies for independently testing pads were assessed using four existing pad designs. One of these methodologies used a flat anvil impact surface, and the other used a modular elastomer pad (MEP) impact surface. Independent pad testing was conducted at three environmental and four impact velocity conditions. These test results were compared to those from complete helmet tests under the same environmental conditions and three of the four impact velocity conditions. This comparison shows that ambient (295 oK) temperature, 3.0 m/s independent pad impacts on a MEP surface account for over 99% of the variation observed in ambient (295 oK) temperature, 3.0 m/s complete system impacts. Under the same conditions, the flat anvil impact surface results account for 92% of the variation seen in complete system impacts. Despite positive results under ambient conditions, independent pad impacts are not a useful predictor of pad suspension system performance under extreme high or low temperatures. For example, hot (327 oK) temperature, 3.0 m/s independent pad impacts on a MEP surface account for only 31% of the variation observed in hot (327 oK) temperature, 3.0 m/s complete system impacts. Under the same conditions, flat anvil impact results account for only 4.4% of the variation seen in system impacts. At extreme temperature conditions, interactions of the helmet or impact surface with the pad suspension system likely contribute significantly to the end result. Independent impacts become progressively less valuable as a predictor of helmet system results as the impact temperature condition becomes increasingly extreme, and future studies will assess alternative test setups that may eliminate this drawback.

15. SUBJECT TERMS **Advanced Combat Helmet; ACH; Pad Suspension System; Head Protection; Helmet; Combat Helmet; Blunt Impact Protection; Helmet Test Method**					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**10**	

testing is simpler than that for the ACH as a whole; thus, savings in addition to material costs may be realized with independent pad suspension evaluation.

The validity of using independent pad suspension evaluation to characterize the performance of a particular pad suspension system was assessed using over six impact conditions on complete ACH's as well as isolated pad suspension systems with four commercial off-the-shelf (COTS) pad suspension systems. The results of these tests show that independent pad impacts may provide a good initial indication of pad suspension system performance. Under certain conditions, impact attenuation results for independent pads accounted for over 99 percent of the observed variation in impact attenuation results for the ACH under similar conditions. However, under other conditions, impact attenuation results for independent pads were poor indicators of the observed variation in impact attenuation results for the ACH.

Figure 1. Advanced Combat Helmet (ACH) with retention strap and seven pad configuration

2. THEORY

For a pad suspension system to have better performance characteristics, it must have one or more of the following: a better pad to helmet interface, a better pad to head interface, or an improved mechanical response to dynamic loading. The integral component of the ACH pad suspension system is the actual pad, and most factors that affect overall pad suspension system performance may be measureable independent of a helmet shell. Independent evaluation of pad performance is quicker and cheaper than system evaluation inside of a helmet. Although it may not capture all interaction factors that affect system performance, independent pad performance, under certain conditions, may be strongly indicative of the actual performance of the pad suspension system. The primary goal of this test procedure is to identify isolated pad test conditions that will allow the accurate evaluation of pad suspension design performance without the need to test a complete ACH.

2.1 Evaluation Model

In this report, the mean peak acceleration is the measure used to determine pad suspension system performance. This measure is the simple average, over several tests, of the peak uniaxial acceleration for each test. The lower the peak acceleration, the better a particular pad attenuated the assessed blunt impact event. For helmet system tests, the peak uniaxial acceleration is measured at the center of mass for a standard U.S. Department of Transportation (DOT) headform, and, for independent pad tests, at the center of mass for a hemispherical impactor [5].

When mean peak acceleration for helmet system tests (S-DOT) is plotted against impact velocity, the resultant data points show strong evidence for quadratic or higher order nonlinearity, see Figure 2. In contrast, when mean peak acceleration for independent pad tests (I-MEP) is plotted against impact velocity, the relationship between impact velocity and mean peak acceleration is essentially linear, see Figure 2. For MEP impacts, over 99 percent of the variation in mean peak acceleration is explained by a linear relationship to impact velocity. Because the respective S-DOT and I-MEP mean peak acceleration to impact velocity curves behave differently, it is not useful to compare independent pad results to helmet system results across a range of velocities. Rather it is only useful to compare the results from independent pad tests at a particular impact velocity to that of helmet system tests at a particular impact velocity. Figure 2 identifies such a "velocity slice" for comparison between S-DOT tests and I-MEP tests with a blue box.

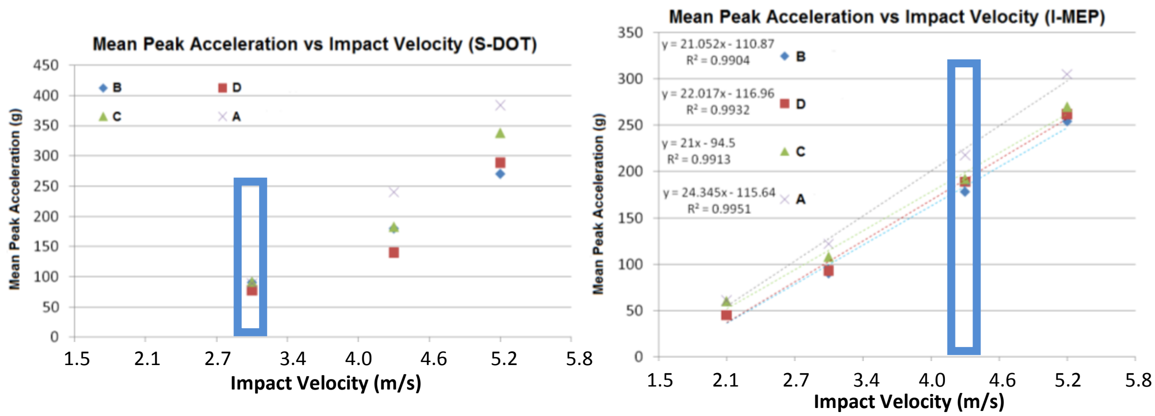

Figure 2. Mean peak acceleration for all temperature conditions shows strong evidence of nonlinearity for S-DOT impacts (left) and linearity for I-MEP impacts (right).

The velocity slice for independent pad tests does not need to be at the same velocity as that for the helmet system. The independent pad tests are very different from the helmet system tests, and there is no reason to believe that the results of independent pad tests would better model helmet system tests if they are conducted at the same impact velocity. The goal is to find the independent pad impact velocity that provides results that best match that seen in helmet systems at some target velocity. Since the current purchase description for the ACH requires a particular impact attenuation capability at an impact velocity of ten feet per second, this is the initial helmet system impact velocity of interest [6].

2.2 Linear Regression

The accuracy of individual pad impact predictions of system performance was assessed using a standard linear regression. System impact results were regressed against individual pad impacts. The resultant linear fit is of the form:

$$\bar{a}_{system} \approx \beta_1 \cdot \bar{a}_{indivdual} + \beta_{0,} \tag{1}$$

where the mean acceleration of the DOT headform in the system ($\bar{a}_{system}$) for a particular impact condition is approximately equal to the mean acceleration of the hemispherical impactor on the individual pad test ($\bar{a}_{individual}$) for a particular impact condition times a constant (β_1) plus an intercept constant (β_0).

2.3 Error Analysis

The main variables of interest for the linear regression in Equation 1 are: environmental temperature, impact velocity, and peak acceleration.[a] Conditioning temperatures for test samples were maintained within ±5°K for cold (263°K) and hot (327°K) conditions and within ±4°K for ambient (295°K) conditions. Measurements for these temperatures were within ±3.6°K of the actual value for all conditions. Impact velocities were measured within ±3 percent of the stated impact velocity and actual values were within ±0.02 meters per second of the measured value for all tests [7]. Peak acceleration was measured in terms of standard gravitational equivalents, where 1 g is equal to 9.81 meters per second squared.

The primary sources of error for the mean peak acceleration are broken into two categories: random and systematic. The random error is defined here as that error associated with random variation in sample performance (intra-sample and inter-sample) as well as random variation in apparatus measurement. Systematic error is defined here as that error associated with systematic bias in sample performance and systematic bias in apparatus measurement. The systematic bias in sample performance is not estimated. The systematic bias in apparatus measurement is estimated to be no greater than the calibrated error in acceleration measurement. Three independent laboratories were used to obtain acceleration measurements: Labs 1, 2, and 3. Lab 1's calibrated error is 1.2 percent (±6 g at 500 g), Lab 2's calibrated error is ±3.2 g,

[a] Additional variables such as relative humidity were controlled or observed but are not reported in this report.

and Lab 3's calibrated error is ±2.84 g. The acceleration results for all three laboratories are combined into the reported average peak acceleration, and the maximum systematic error, $E_{systematic}$, is approximated as:

$$E_{systematic} \approx \pm 3.2 \text{ g for g} \leq 267 \text{ and } E_{systematic} \approx \pm 1.2\% \text{ g for g} > 267. \quad (2)$$

The maximum random sample error, E_{random}, was estimated using the standard error of the mean by the following method:

$$E_{random} \approx t^* \cdot \left[\frac{\sigma_{peak\ g}}{\sqrt{a}}\right] = t^* \cdot [S.E.], \quad (3)$$

where $\sigma_{peak\ g}$ is the standard deviation of the measured peak acceleration values for a particular temperature condition and impact velocity, a is the number of data points observed, t^* is equal the value obtained from a two tailed Student's t-distribution for a 95 percent confidence interval with a-2 degrees of freedom, and *S.E.* is the standard error of the mean. Because it is assumed that the systematic measurement error and the random sampling error are independent and uncorrelated, the maximum expected error in mean peak acceleration values is calculated by:

$$E_{max} \approx \sqrt{E_{random}^2 + E_{systematic}^2}, \quad (4)$$

where E_{max} is the maximum total error, $E_{systematic}$ is the maximum systematic error, and E_{random} is the maximum random error as calculated by Equation 2 and Equation 3, respectively.

3. METHOD

The primary method of data collection for this report is detailed in the 2008 Joint Live Fire Advanced Combat Helmet Report. Except where otherwise stated, all blunt impacts performed for this report were done in accordance with the Advanced Combat Helmet Purchase Description (CO/PD-05-04) as well as the U.S. Department of Transportation (DOT) Federal Motor Vehicle Safety Standard (FMVSS) Number 218: Motorcycle Helmets. Four variant COTS pad suspension systems (labeled manufacturer A, B, C, and D) were used in the independent pad tests and the helmet system tests (see Figure 3). All testing was performed with a monorail drop tower (see Figure 4) at three conditioning temperatures: 263 ±5°K, 295 ±4°K, and 327 ±5°K. Linear accelerometers mounted at the center of the drop tower ball socket were used to collect acceleration-time history data of the hemispherical impactor for independent pad tests and of the DOT headform for helmet system tests. Over 5,040 impacts were conducted on crown pad samples, and over 6,804 impacts were conducted on over 486 complete helmets.

Figure 3. Commercial off the shelf (COTS) pad suspension systems

Independent pad impacts were conducted with a hemispherical impactor on the crown pad (circular pad shown in Figure 1) at a velocity of 2.1, 3.0, 4.3, and 5.3 meters per second (±3%). Each independent test consisted of repeated impacts with a 45 ±15 second recovery time between impacts. A total of three pads were tested at each temperature with ten repeated impacts at ambient (295 ±4°K) temperature conditions and five repeated impacts at the cold (263 ±5°K) and hot (327 ±5°K) temperature conditions. If impact conditions for a particular sample reached acceleration levels that exceeded that which could be recorded safely, the remaining repeated impacts were not conducted for that sample.

Helmet system impacts were conducted onto a hemispherical impactor with a fully assembled ACH fitted to a DOT size "C" headform at a velocity of 3.0, 4.3, and 5.3 meters per second (±3%). All helmet system impacts examined for this study were performed on size large helmets from the same manufacturer.

Each tested helmet was impacted two times at seven locations on a hemispherical anvil as required by the ACH purchase description. The impacted locations are the: front, back, left side, right side, lower left nape, lower right nape, and crown as defined in CO/PD-05-04 [6]. The time between repetitive impacts was 90 ±30 seconds for all helmet system impacts.

3.1 Apparatus

The apparatuses used to collect the data presented in this report are shown below in Figure 4. Two test surfaces were used to evaluate individual pad response. The first of these surfaces is a flat anvil with a hemispherical impactor, and the second is a Modular Elastomer Pad (MEP) with a hemispherical impactor. The flat anvil and hemispherical impactor combination most closely replicates the impact strategy used when testing helmets in accordance with ACH CO/PD 05-04; however, the extreme stiffness of the flat anvil and the sharp radius of the hemispherical impactor induce highly concentrated loads in the padding material that likely does not occur in a fully assembled helmet. The MEP (shown in Figure 5) is composed of a resilient, one inch thick, highly stable, molded material [8]. The MEP is often used for nondestructive testing of sports helmets, and the MEP surface allows better distribution of loads induced by the hemispherical impactor on a test pad than does the flat anvil. The tests conducted on the MEP were conducted on the circular crown pad from each of the four manufactures (A, B, C, and D) at four different impact velocities: 2.1, 3.0, 4.3, and 5.3 m/s. The tests conducted on the flat anvil were performed at the two lower impact velocities: 2.1 and 3.0 m/s. Each of these target velocities were held to a tolerance of plus or minus three percent. The flat anvil testing was conducted only at the lower velocities because the higher velocities yielded impact-induced accelerations that posed a risk of damage to the flat anvil surface and the pad systems tested. Neither of these individual impact setups present an obvious match to ACH system impact setup; however, the results from these setups provide a baseline for further improvements.

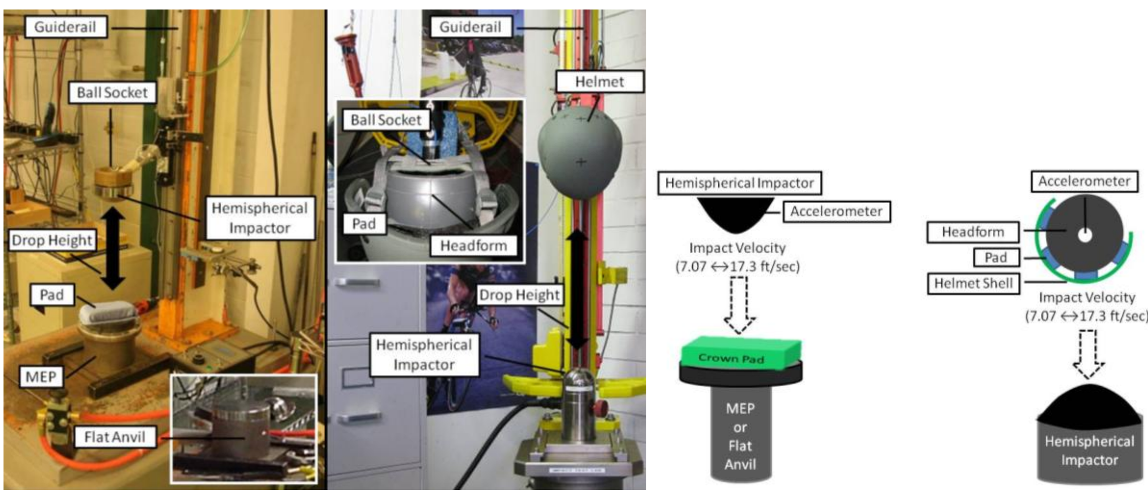

Figure 4. Independent pad test setup (left and center right) and system test setup (right and center left)

Figure 5. MEP monorail drop test setup with a hemispherical impactor (left and center left). Flat anvil monorail drop test setup with a DOT headform (right and center right).

3.2 Measured Data

Measured variables include: impact velocity, drop height, drop energy, impactor mass, laboratory temperature, laboratory humidity, pad conditioning temperature, pad conditioning humidity, and peak acceleration at the center of mass. Some labs measured variables in addition to those listed and the equipment used to acquire and process each measured variable differed between laboratories. Table 1 shows mean peak acceleration (MPA) values for each impact velocity (v), sample conditioning temperature (T), pad suspension system variant (Mfg), and type of test (Type). Type I-MEP is an independent impact test with the MEP surface. Type I-FA is an independent impact test with the flat anvil surface. Type S-DOT is a system impact test with the DOT headform. The number of samples (#), the total number of data points (a), and the max total error (E) for each condition is also listed.

Table 1. Summarized mean peak acceleration (MPA) values for all conditions

Mfg	T (^{o}K)	v (m/s)	Type	#	a	MPA (g)	E (±g)	Type	#	a	MPA (g)	E (±g)	Type	#	a	MPA	E (±g)
A	263	2.1	I-MEP	9	45	53.94	3.67	I-FA	9	45	118.76	12.98					
B	263	2.1	I-MEP	9	45	55.87	3.58	I-FA	9	45	60.22	3.57					
C	263	2.1	I-MEP	9	45	63.64	3.53	I-FA	9	45	79.87	4.04					
D	263	2.1	I-MEP	9	45	46.98	3.37	I-FA	9	45	49.39	3.35					
A	295	2.1	I-MEP	12	120	61.63	3.26	I-FA	12	120	200.02	9.97					
B	295	2.1	I-MEP	12	120	35.88	3.23	I-FA	12	120	43.06	3.45					
C	295	2.1	I-MEP	12	120	58.11	3.24	I-FA	12	120	99.29	4.22					
D	295	2.1	I-MEP	12	120	45.01	3.28	I-FA	12	120	49.86	3.37					
A	327	2.1	I-MEP	9	45	65.68	3.68	I-FA	9	45	264.04	16.10					
B	327	2.1	I-MEP	9	45	56.12	3.97	I-FA	6	30	148.93	18.87					
C	327	2.1	I-MEP	9	45	59.56	3.32	I-FA	9	45	137.19	7.99					
D	327	2.1	I-MEP	9	45	44.28	3.40	I-FA	9	45	59.06	3.96					
A	263	3.0	I-MEP	9	45	113.58	4.51	I-FA	9	17	466.58	73.09	S-DOT	12	168	78.21	4.08
B	263	3.0	I-MEP	9	45	96.13	5.08	I-FA	9	45	123.60	10.20	S-DOT	12	168	95.03	4.51
C	263	3.0	I-MEP	9	45	105.11	3.79	I-FA	9	45	201.02	16.91	S-DOT	12	168	96.97	4.07
D	263	3.0	I-MEP	9	45	93.61	7.20	I-FA	9	45	122.65	13.32	S-DOT	18	252	75.21	3.70
A	295	3.0	I-MEP	12	120	124.05	3.29	I-FA	12	12	549.51	41.81	S-DOT	12	168	90.27	4.50
B	295	3.0	I-MEP	12	120	79.99	3.52	I-FA	12	120	200.04	12.96	S-DOT	12	168	69.75	3.70
C	295	3.0	I-MEP	12	120	105.97	3.28	I-FA	12	120	336.39	9.07	S-DOT	12	168	82.13	3.54
D	295	3.0	I-MEP	12	120	92.58	3.51	I-FA	12	120	248.11	15.61	S-DOT	18	252	75.57	3.62
A	327	3.0	I-MEP	9	45	126.04	3.46	I-FA	6	6	624.43	68.28	S-DOT	12	168	98.90	4.91
B	327	3.0	I-MEP	9	45	110.22	3.84	I-FA	12	36	388.96	43.49	S-DOT	12	168	107.45	4.72
C	327	3.0	I-MEP	9	45	114.22	3.49	I-FA	9	45	407.83	14.59	S-DOT	12	168	95.86	4.51
D	327	3.0	I-MEP	9	45	93.59	3.60	I-FA	9	38	360.01	25.00	S-DOT	18	252	87.07	4.60
A	263	4.3	I-MEP	9	45	207.29	5.23						S-DOT	12	168	183.53	13.49
B	263	4.3	I-MEP	9	45	182.43	11.85						S-DOT	12	168	131.51	6.08
C	263	4.3	I-MEP	9	45	172.12	3.94						S-DOT	12	168	162.43	5.23
D	263	4.3	I-MEP	9	45	192.51	25.77						S-DOT	18	252	140.89	9.93
A	295	4.3	I-MEP	12	120	219.66	3.55						S-DOT	12	168	229.80	16.51
B	295	4.3	I-MEP	12	120	166.10	3.77						S-DOT	12	168	139.02	6.78
C	295	4.3	I-MEP	12	120	195.37	3.39						S-DOT	12	168	177.74	11.16
D	295	4.3	I-MEP	12	120	182.44	4.02						S-DOT	27	378	143.94	8.43
A	327	4.3	I-MEP	9	45	224.68	3.96						S-DOT	12	168	308.16	22.83
B	327	4.3	I-MEP	9	45	203.65	4.31						S-DOT	12	167	268.64	18.27
C	327	4.3	I-MEP	9	45	204.74	3.95						S-DOT	12	168	209.05	13.43
D	327	4.3	I-MEP	9	45	204.69	22.61						S-DOT	18	252	203.58	15.67
A	263	5.3	I-MEP	9	45	296.78	5.89						S-DOT	12	161	402.96	33.07
B	263	5.3	I-MEP	9	45	253.82	16.15						S-DOT	12	168	207.39	14.74
C	263	5.3	I-MEP	9	45	239.21	5.10						S-DOT	12	166	271.59	14.42
D	263	5.3	I-MEP	9	45	247.98	12.37						S-DOT	18	251	217.07	15.77
A	295	5.3	I-MEP	12	120	307.07	4.31						S-DOT	12	168	360.50	20.84
B	295	5.3	I-MEP	12	120	245.83	4.51						S-DOT	12	168	237.99	16.95
C	295	5.3	I-MEP	12	120	276.65	3.98						S-DOT	12	168	297.15	19.26
D	295	5.3	I-MEP	12	120	267.22	4.69						S-DOT	18	252	318.93	20.19
A	327	5.3	I-MEP	9	45	308.22	5.27						S-DOT	12	154	389.57	19.20
B	327	5.3	I-MEP	9	45	275.44	5.86						S-DOT	12	168	364.43	19.00
C	327	5.3	I-MEP	9	45	282.45	4.67						S-DOT	12	157	452.48	22.34
D	327	5.3	I-MEP	9	45	263.65	4.50						S-DOT	21	274	360.34	16.29

3.3 Error Analysis

The max total error was calculated using Equation 4. This margin of error is as low as 1.4 percent for some conditions; however, it is as high as 15.7 percent under others. On average, the total margin of error for the values presented in Table 1 above is 5.5 percent. The highest error conditions are those involving flat anvil impacts at high velocities and extreme temperature conditions. Some of the increase in variation under those conditions is resultant from large increases in measured peak acceleration for repeated impacts.

Some degradation in pad performance was observed for repeated independent pad impacts as well as for repeated helmet system impacts. These increases are, in part, caused by permanent damage to the impacted pad. The rate of damage to the impacted pad increases with increased stress concentrations. This effect is more pronounced under extreme temperature conditions and at higher impact velocities. The change in peak acceleration from the first to tenth impact was generally lower with the MEP than with the flat anvil. This may be due to higher load concentrations and subsequent greater material damage incurred during the flat anvil impacts. The flat anvil results may provide an exaggerated assessment of potential performance degradation due to concentrated loading for each pad type; whereas, the MEP may provide a better measure of actual helmet system performance for each pad type than the flat anvil.

Three independent testing laboratories were used for all testing. A control test (same temperature, impact velocity, and pad suspension system manufacturer) was completed for all three locations, and the results of this control test indicated that there was a statistically significant difference in the impact velocity at each lab. Although the impact velocity differences for each lab were within the allowed three percent margin of error, the statistically significant variation in impact velocity between the labs created a statistically significant variation in measured peak accelerations resultant from those impact velocities. If a velocity interaction term is included in all calculations, this variation disappears; however, a velocity interaction term was not used during the analysis presented here. Thus, all presented conclusions may contain a small error factor propagated by accepted differences in inter-laboratory impact conditions.

In addition to velocity differences, each laboratory had a different maximum accurately recordable acceleration. Lab 2's maximum accurately recordable acceleration was 500 g (with some signal clipping that starts at 480 g). Lab 3's max was 750 g, and Lab 1's max was 500 g (with the ability to record higher at a significant reduction in accuracy). Some of the data gathered for the higher velocity impacts, in particular the 5.3 m/s MEP impacts and the 10 fps flat anvil impacts, exceeded this limit for one or more laboratories. The expected error for these conditions is greater than that calculated by Equation 4. Measurements affected by such instrumentation limits are lower than the actual value. Values heavily affected by laboratory instrumentation limits are highlighted blue in Table 1.

4. RESULTS

The measured data presented in Table 1 was regressed in accordance with Equation 1. Table 2 contains the results of this regression separated by environmental condition, impact velocity, and independent pad test setup (flat anvil or MEP). The regression values for 5.3 m/s helmet system impacts were not presented due to the large degree of error associated with instrumentation measurement limits for that test condition. Although the acceleration values for 3.0 m/s flat anvil impacts are also influenced by the same instrumentation error, regressions based on these values were included for reference only. Reference only values are highlighted in blue in Table 2. Table 2 is broken down by the velocity of the helmet system test (V_{sys}) that is being evaluated for predictability by the one of the types (I-Type) of independent pad tests: MEP (I-MEP) or flat anvil (I-FA). Because temperature has a large effect on the viscoelastic properties of the ACH pad suspension system, each regression is also segregated by sample temperature (T) condition. The coefficients defined in Equation 1 (β_1 and β_0) are listed, and the coefficient of determination (R^2) also is reported for each regression. The results listed in Table 2 for 3.0 m/s system impacts under ambient (295 $\pm 4^oK$) and hot (327 $\pm 5^oK$) conditions are displayed graphically in Figure 6.

Figure 6 depicts mean DOT headform accelerations due to a 3.0±0.1 m/s impact of a size large helmet onto a hemispherical impactor versus average hemispherical impactor accelerations due to a 2.1 ±0.1 m/s, a 3.0 ±0.1 m/s, a 4.3 ±0.1 m/s, or a 5.3 ±0.2 m/s impact onto a crown pad and MEP. Mean values are collated by pad manufacturer (i.e. each data point represents the values obtained from samples of one of the four pad suspension systems used for this testing). All impacts shown occurred under ambient temperature conditions (295 $\pm 4^oK$), and error bars depict the max estimated error as calculated by Equation 4.

Table 2. Summarized regression results for helmet system impacts at 3.0 and 4.3 meters per second

V_{sys} (m/s)	T (°F)	V_{ind} (fps)	I-Type	β_0	β_1	R^2	I-Type	β_0	β_1	R^2
3.0	295	2.1	I-MEP	43.6	0.71	0.9304	I-FA	68.1	0.12	0.9085
3.0	295	3.0	I-MEP	32.4	0.47	0.9997	I-FA	61	0.06	0.9415
3.0	295	4.3	I-MEP	5.18	0.39	0.9942				
3.0	295	5.3	I-MEP	-14.5	0.34	0.9752				
3.0	263	2.1	I-MEP	9.14	1.4	0.7303	I-FA	90.4	-0.05	0.0206
3.0	263	3.0	I-MEP	70.6	0.16	0.0099	I-FA	92	-0.02	0.1277
3.0	263	4.3	I-MEP	205	-0.63	0.7056				
3.0	263	5.3	I-MEP	144	-0.22	0.2602				
3.0	327	2.1	I-MEP	66.8	0.54	0.3349	I-FA	89.4	0.05	0.276
3.0	327	3.0	I-MEP	58.3	0.35	0.3135	I-FA	90.8	0.01	0.0441
3.0	327	4.3	I-MEP	83.1	0.07	0.0067				
3.0	327	5.3	I-MEP	54.3	0.15	0.1165				
4.3	295	2.1	I-MEP	16.4	3.11	0.7857	I-FA	116	0.58	0.995
4.3	295	3.0	I-MEP	-43.3	2.15	0.9367	I-FA	82.94	0.27	0.989
4.3	295	4.3	I-MEP	-169	1.79	0.9351				
4.3	295	5.3	I-MEP	-258	1.57	0.9111				
4.3	263	2.1	I-MEP	105	0.9	0.0705	I-FA	99.6	0.71	0.8805
4.3	263	3.0	I-MEP	-151	3.02	0.8637	I-FA	124	0.13	0.8624
4.3	263	4.3	I-MEP	14.6	0.74	0.2295				
4.3	263	5.3	I-MEP	-4.9	0.61	0.4589				
4.3	327	2.1	I-MEP	22.7	3.98	0.5117	I-FA	166	0.53	0.803
4.3	327	3.0	I-MEP	-68.4	2.84	0.5802	I-FA	96.7	0.34	0.6672
4.3	327	4.3	I-MEP	-557	3.84	0.607				
4.3	327	5.3	I-MEP	-346	2.1	0.6249				

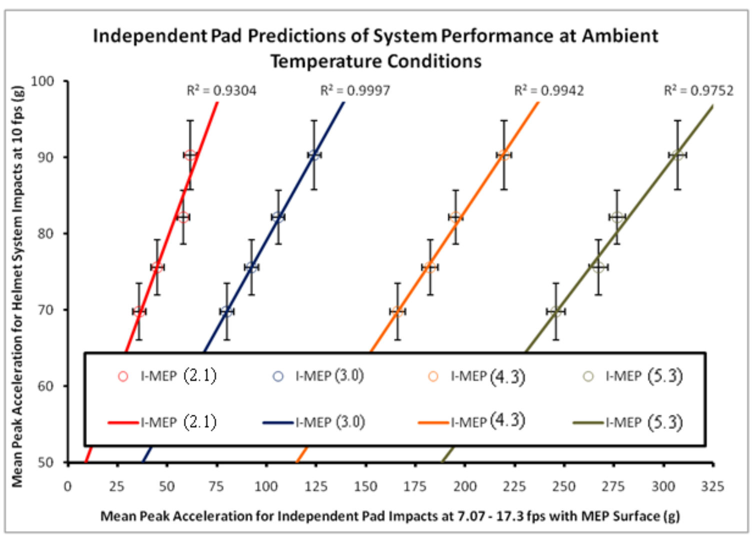

Figure 6. Ambient temperature 3.0 m/s system impact regressions using independent MEP impact results

5. DISCUSSION

As shown in Figure 6, independent pad impacts are good predictors of pad performance at ambient temperature conditions. For all ambient conditions tested (including both the MEP and the flat anvil independent configurations), the lowest coefficient of determination for regressions of helmet system impacts at 3.0 m/s was 0.79. On average it was 0.94 with a high of 0.9997. The 0.79 was a MEP impact at

2.1 m/s modeling a 4.3 m/s helmet system impact. The MEP impact at 2.1 m/s likely did not expose the pad to enough energy to effectively replicate its performance in a helmet system exposed to a 4.3 m/s impact. These results show that there is great promise for the future use of individual pad impacts to more rapidly screen candidate pad suspension systems and to reduce the overall cost associated with pad suspension system testing.

Despite positive results for ambient temperature impact conditions, the extreme temperature condition results were not consistent with the ambient findings. For example, hot (327^{o}K) temperature, 3.0 meters per second independent pad impacts on a MEP surface account for only 31 percent of the variation observed in hot (327^{o}K) temperature, 3.0 meters per second complete system impacts. Under the same conditions, the results from the flat anvil impact surface account for only 4.4 percent of the variation seen in those same system impacts. Most extreme temperature conditions showed no significant trend between the independent pad results and that of helmet systems. There are several possible explanations for this.

First, the testing process for independent tests differed between the ambient and cold/hot temperature conditions. Each independent pad sample tested at ambient temperature conditions was impacted ten times in succession. The time interval between impacts was 45 ±30 seconds. At hot or cold temperature conditions, each sample tested was impacted only five times with the same time interval between impacts. If test samples are damaged during impact such that their performance declines over successive impacts, then this difference in test method could change the nature of the results shown. Despite this possibility, the test results show that performance declines were sharper for the extreme temperature conditions despite the lower number of impacts. Also, regressions performed on data sets limited by impact number show no significant improvement in extreme temperature condition prediction capability.

Second, thermodynamic interactions for independent pad testing are significantly different than that for helmet systems. Upon removal from conditioning chambers, the temperature condition of an independent pad sample will rapidly deviate from the temperature condition of the helmet system. This difference in sample temperature conditions was not accommodated through repetitive return of samples to conditioning values between impacts. This may have had a moderate effect on regression results.

Third, it is reasonable to assume that some damage occurs with each impact in either test setup. Under certain circumstances, this damage is insignificant. Under others, it is significant. If the damage mode for pad suspension systems is sensitive to temperature and load, it may be possible for a pad to behave significantly different under independent loading versus helmet system loading at extreme temperature conditions (hot or cold). Under this scenario, the acceleration values obtained at conditions resulting in increased pad damage should exhibit greater variability. In turn, this variability will be evident in the error calculation for such conditions. Coupled with temperature variations between independent and system testing, this could have a strong effect on results.

Finally, the influence of the helmet shell in helmet system impacts may be greater under extreme temperature conditions than under ambient conditions. If the helmet becomes significantly more compliant under high temperatures or significantly stiffer under low temperatures than under ambient temperature conditions, the helmet shell may vary the test results in a manner that is not mirrored by the independent pad tests. Further testing of the thermal dependency of helmet shell properties must be conducted before the validity of this hypothesis can be assessed.

There are additional test setups that may eliminate the drawback of pad interaction caused by the hemispherical impactor on the MEP and of high stress concentrations caused by the hemispherical impactor on the flat anvil. One such setup is a flat or ellipsoidal impactor with a flat anvil. Although these additional test setups were not tested for this report, future studies may examine these test setups for improved accuracy in pad performance predictions over that given by the hemispherical impactor with either the flat anvil or the MEP.

6. CONCLUSIONS

The Advanced Combat Helmet (ACH) is the primary head protection for the dismounted American soldier. The ACH has seven major components, and the pad suspension system is the primary attenuator of blunt impacts to a Soldier's head. Quantification of improvements to helmet pad suspension systems currently requires blunt impact system tests that are costly and time consuming. However, the principle component of the ACH pad suspension system is the pad itself, and independent pad performance should be strongly indicative of the actual performance of the complete ACH system. Two potential methodologies for

independent pad testing that would quickly and inexpensively evaluate the performance of pad suspension designs without testing them inside of a helmet were assessed for this report.

Two independent pad impact surfaces and four COTS pad suspension system designs were used to evaluate the use of independent pad impacts to predict helmet system impact results. One surface chosen was a flat anvil impact surface, and the other was a modular elastomer pad (MEP) impact surface. The test methodology for each surface was otherwise identical. Independent pad testing was conducted at three environmental and four impact velocity conditions and the results of these tests were compared to those from complete helmet tests under the same three environmental conditions and three of the four impact velocity conditions.

Over 5,040 impacts were conducted on crown pad samples, and over 6,804 impacts were conducted on over 486 complete helmets. Analysis of the results from these impacts shows that the MEP impact surface may be more capable of predicting pad suspension system performance inside of a helmet than the flat anvil surface. Ambient (295^{o}K) temperature, 3.0 meters per second independent pad impacts on a MEP surface account for over 99 percent of the variation observed in ambient (295^{o}K) temperature, 3.0 meters per second complete system impacts. Under the same conditions, the flat anvil impact surface results account for 92 percent of the variation seen in those same system impacts.

Despite these positive results, neither surface is a useful predictor of pad suspension system performance under extreme conditions such as high impact velocity or extreme high or low temperatures. For example, hot (327^{o}K) temperature, 3.0 meters per second independent pad impacts on a MEP surface account for only 31 percent of the variation observed in hot (327^{o}K) temperature, 3.0 meters per second complete system impacts. Under the same conditions, the results from the flat anvil impact surface account for only 4.4 percent of the variation seen in those same system impacts.

At extreme temperature and velocity conditions, interactions of the helmet or impact surface with the pad suspension system likely contribute significantly to the end result. Since these interactions vary greatly between the independent impact and helmet impact results, the independent impacts become progressively less valuable as a predictor of helmet system results as the impact temperature condition becomes increasingly extreme. There are additional test setups that may eliminate this drawback, and future studies will examine these test setups for improved accuracy in predicting pad performance.

7. REFERENCES

[1] Program Executive Office – Soldier. "Purchase Description, Helmet, Advanced Combat (ACH)." CO/PD-05-04. (Technical Management Division, PM Soldier Equipment, Fort Belvoir, VA, 30 October 2007).

[2] Department of the Army. "Technical Operator's Manual for Advanced Combat Helmet (ACH)." TM 10-8470-204-10. (Headquarters, Department of the Army, Washington, DC, 14 March 2008) pp. 0002-1-0002-17.

[3] Masters, K., Perritt, C., Haynes, N, Halls, V, Hopping, J, Perry, C, Bass, C, and Eckels, S., 2008 Joint Live Fire Advanced Combat Helmet Report (Defense Technical Information Center, Fort Belvoir, VA, 2009) pp. 12-25.

[4] Department of the Army. "Technical Operator's Manual for Advanced Combat Helmet (ACH)." TM 10-8470-204-10. (Headquarters, Department of the Army, Washington, DC, 14 March 2008) pp. 0005-1-0006-2.

[5] U.S. Department of Transportation. "Laboratory Test Proceedure for Motorcycle Helmets." FMVSS No. 218. TP-218-06. (National Highway Traffic Safety Administration, Office of Vehicle Safety Compliance, Washington DC, 30 November 2006) pp. 21.

[6] Program Executive Office – Soldier. "Purchase Description, Helmet, Advanced Combat (ACH)." CO/PD-05-04. (Technical Management Division, PM Soldier Equipment, Fort Belvoir, VA, 30 October 2007) pp. 32.

[7]U.S. Department of Transportation. "Laboratory Test Proceedure for Motorcycle Helmets." FMVSS No. 218. TP-218-06. (National Highway Traffic Safety Administration, Office of Vehicle Safety Compliance, Washington DC, 30 November 2006) pp. 14.

[8]Becker, E. Helmet Development and Standards, Excerpt from Frontiers in Head and Neck Trauma Clinical and Biomedical (Snell Memorial Foundation, North Highlands, CA) pp. 22.